Alternative Paths to Fusion

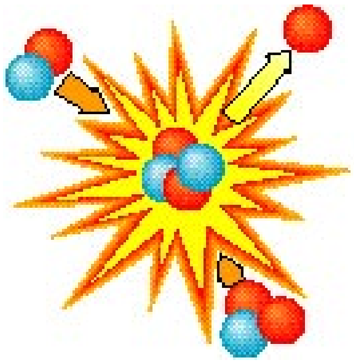
...the energy source of the sun and stars

Why Pursue Multiple Paths?

Fusion is the energy source of the sun and stars. In fusion, two light nuclei (such as hydrogen) combine into one new nucleus (such as helium) and release enormous energy in the process. On earth, fusion has the potential to be an abundant and attractive source of energy for the future. However, creating fusion conditions on earth—and tapping that energy in practical forms—continues to challenge the world's scientists, although tremendous progress has been made.

Many potential routes

One approach to fusion uses magnetic fields to confine a plasma of hydrogen isotopes long enough for fusion to occur. Although most recent magnetic fusion research has focused on the tokamak (a doughnut-shaped configuration with magnets running through the central "hole"), there are other alternatives that could possibly lead to smaller reactors and a cheaper cost of electricity. One way to distinguish these alternatives is by their magnetic topology, as described in this brochure. That topology is intimately related to how these concepts work.



A fusion reaction of two isotopes of hydrogen—deuterium and tritium—into an isotope of helium and a neutron, with a total energy release of 17.6 million electron volts.

Another major approach to fusion (inertial fusion energy) employs a "driver" to focus beams of either accelerated ions or laser light upon hydrogen-filled "targets." The resulting pressure from the imploding target squeezes the nuclei together so that fusion reactions occur.

Other concepts combine these two approaches or fall outside of them. Listed below are fusion concepts that are, or have been, under study at some level in the world fusion program. Some of these approaches, such as the tokamak and standard inertial fusion, have a considerable knowledge base. Others have only been proposed at the conceptual level.

Advantages of diverse research

The question is: Which configurations will ultimately prove the most practical for producing cost-effective electricity? To answer the question, we should pursue all promising approaches, which will lead to scientific richness and cross-fertilization of ideas.

In pursuing multiple paths, we can maximize the probability of success in developing an attractive fusion power plant. Researching different concepts will broaden the understanding of fusion science and will lead to cross-fertilization. Each path involves different science and different technologies, and the stumbling block in one path may not occur with another route.

Pursuing various physics solutions in an innovative, diverse fusion program is a sound investment of research dollars to improve both the economics of fusion reactors and our understanding of plasma science for other purposes.

Alternative Fusion Concepts

Low-density magnetic confinement
- Standard field-reversed configuration*
- Large-orbit field-reversed configuration
- Spheromak*
- Spherical torus*
- Reversed-field pinch*
- Conventional and advanced tokamak
- Stellarator*
- Mirror

Inertial confinement fusion
- Standard inertial fusion (driven by heavy ions or lasers)*
- Advanced, fast-ignition systems
- Magneto-inertial concepts*

High-density magnetic confinement
- Pulsed Z-pinches (fiber, laser-assisted, staged pinches)
- Plasma foci
- Continuous flow pinches
- Wall-confined, magnetically-insulated concepts*

Non-thermonuclear and miscellaneous
- Inertial electrostatic confinement
- Colliding beam systems*
- Coulomb barrier circumvention concepts

**Discussed in this brochure*

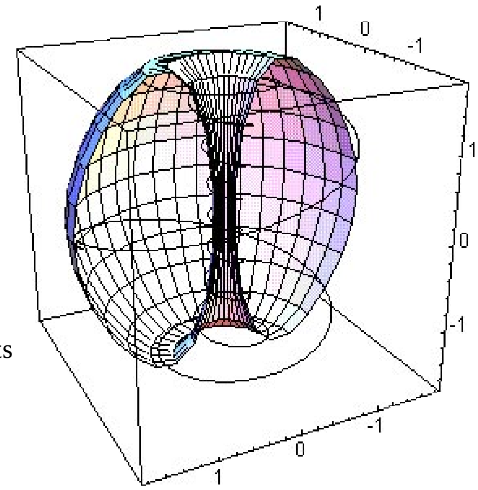
Spherical Torus

Magnetic topology

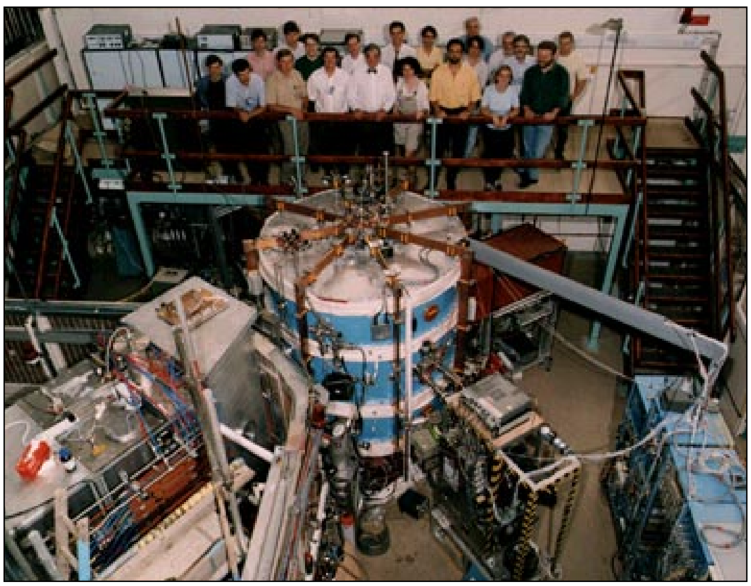
The spherical torus is a tokamak with a minimal "hole" through it, achieved by eliminating the solenoid magnetic coils, normally located there, that induce current in the plasma. The resulting low aspect ratio (major-to-minor plasma radius) plasma has performance advantages but requires a separate means to produce toroidal plasma current. Also, the legs of each toroidal field coil pass through the hole and are subjected to intense neutron radiation, so that superconducting magnets must be avoided.

Advantages

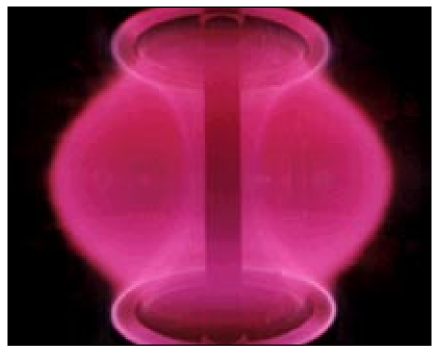
- Small size and low cost.
- Low magnetic field and power.
- High ratio of plasma pressure to magnetic field pressure.
- Ease of maintenance (the magnets can be jointed).



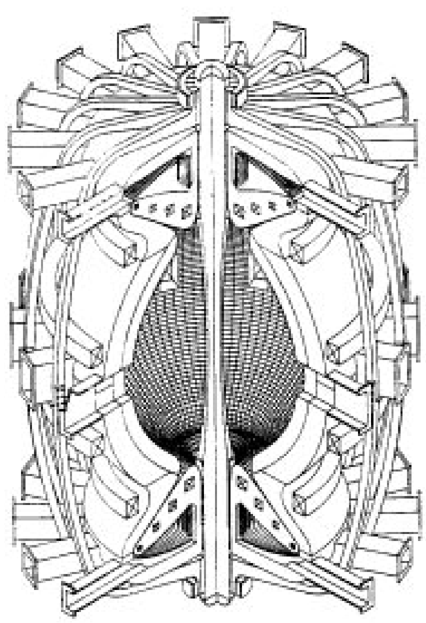
Experiments



The START experiment at Culham, United Kingdom.



A plasma in the START experiment.



A spherical torus core for a power plant.

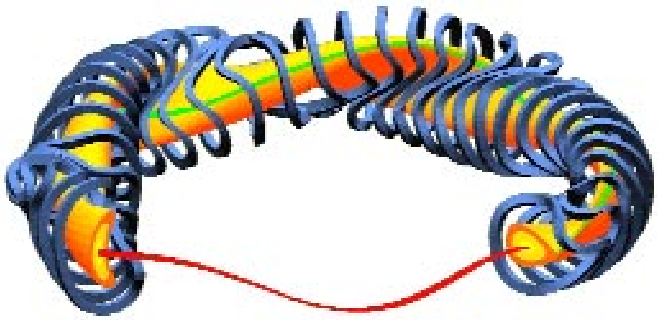
Spherical torus research is under way at:

- Columbia University, New York.
- General Atomics, California.
- Oak Ridge National Laboratory, Tennessee.
- Princeton Plasma Physics Laboratory, New Jersey.
- University of Washington.
- University of Wisconsin.
- UKAEA Culham Laboratory, United Kingdom.
- University of Tokyo and Waseda University, Japan.
- Ioffe Physical-Technical Institute, Russia.
- Instituto de Pesquisas Espocias, Brazil.

The Stellarator

Magnetic topology

The required internal magnetic fields and currents of a stellarator are determined by the external coil geometry. These external coils are not planar but shaped to hold the plasma together without the (net) toroidal plasma current required for the tokamak configuration. The result is a more complex 3-dimensional shape (the tokamak is axisymmetric, or 2-dimensional), but one that does not suffer current-induced plasma disruptions.



(Institute of Plasma Physics, Germany)

Advantages

- No toroidal plasma current is required. Current need not be induced with transformers; thus steady-state operation is inherent to the concept.
- The plasma does not disrupt, so there are no disruption-induced structural forces.

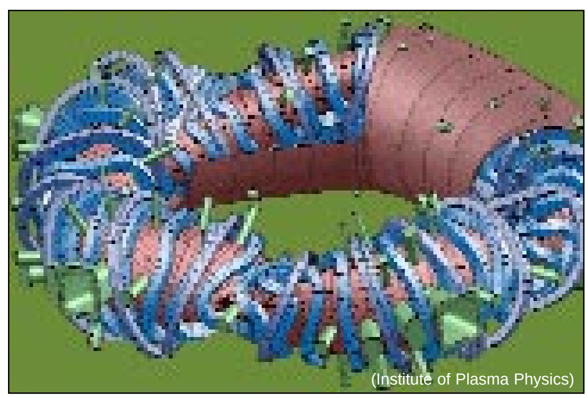
Experiments

- Stellarator research is funded at high levels in Europe and Japan.
- Stellarator performance is close to that of tokamaks.

Two stellarators in the $0.5–1 billion class.

(NIFS)

The helical coil winding machine for the LHD, Japan.



(Institute of Plasma Physics)

A conceptual design of the W7-X, Germany.

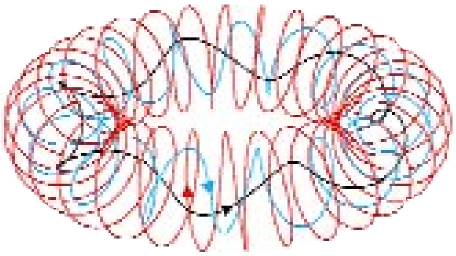
Stellarator research is currently under way at:

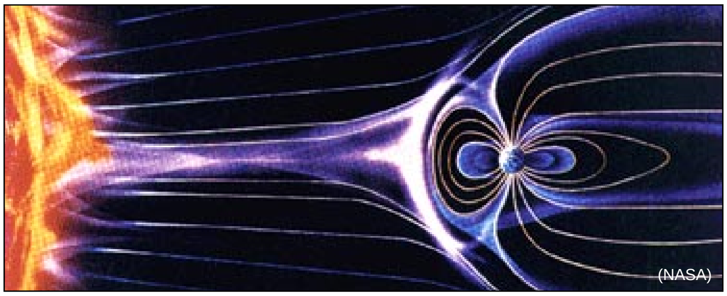
- Oak Ridge National Laboratory, Tennessee.
- Auburn University, Alabama.
- University of Wisconsin, Madison, Wisconsin.
- Australian National University, Australia.
- CIEMAT, Madrid, Spain.
- Kharkov Physico-Technical Institute, Ukraine.
- Kyoto Plasma Physics Laboratory, Japan.
- Institute of General Physics, Russia.
- Institute of Plasma Physics, Germany.
- National Institute for Fusion Science, Japan.

The Reversed-Field Pinch (RFP)

Magnetic topology

The RFP and spheromak are driven towards a state of "minimum energy" by internal dynamos (turbulence driven). In an RFP, the magnetic field lines wind loosely around the torus near the center (black). They wind more tightly as one moves outward (blue), until near the edge of the plasma the toroidal magnetic field reverses and the field lines wind in the reverse direction (red). The internal fields are then larger than the fields at the magnet coils, so RFPs have low-magnetic-field coils but high-fusion-power density.



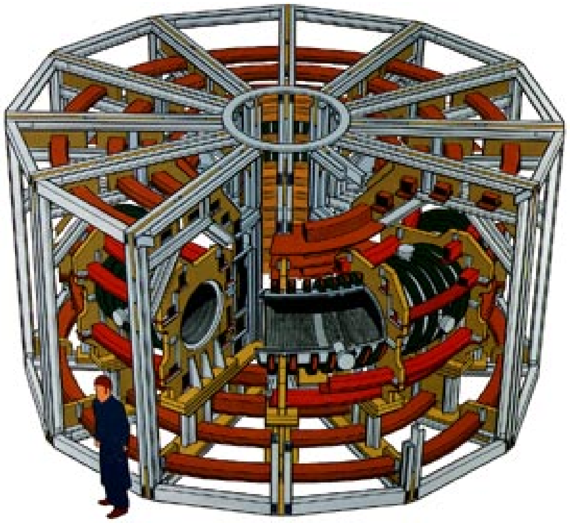


Astrophysical and geophysical dynamos at work. Magnetic-field-generating dynamos are also at work in the RFP and spheromak.

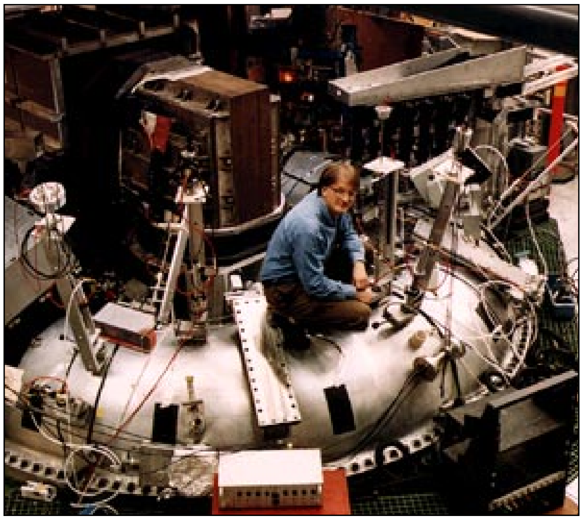
Advantages

- High power density (more compact, better economics).
- Less demanding magnet technology.
- Natural (minimum energy, stable) plasma "state."

Experiments



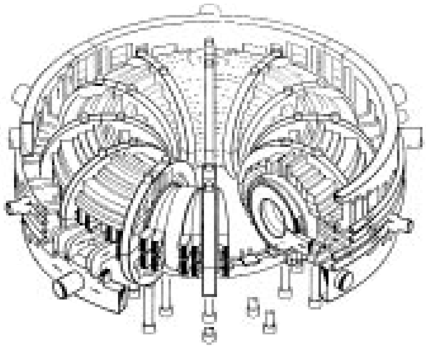
ZT-H, a large RFP experiment at Los Alamos National Laboratory (canceled during construction, 1990).



MST, an RFP experiment under way at the University of Wisconsin.

Other RFP experiments:

- Royal Institute, Stockholm, Sweden.
- Electro-Technical Laboratory, Tsukuba, Japan.
- Istituto Gas Ionizzati del C.N.R., Padova, Italy.



The core of an RFP power plant—conceptual design study at Los Alamos National Laboratory. RFPs have low-magnetic-field coils but high-power fusion density. This means more economical higher-power-density power plants.

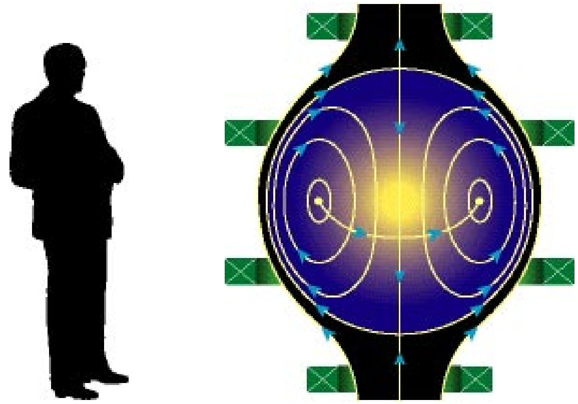
The Spheromak

Magnetic Topology

The spheromak has either little or no “hole” through it, but the dynamo drives the fields and currents to a topology similar to the tokamak. Even with a hole, there is no material (magnets or conductors) through it. As with the RFP, the dynamo drives the configuration towards a stable, minimum-energy state.

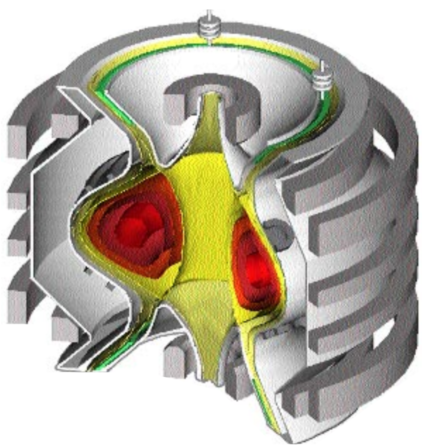
Advantages

- Simple magnet set (circular coils).
- Internal magnetic fields and plasma current generated primarily by the dynamo.
- A compact, less expensive power plant.

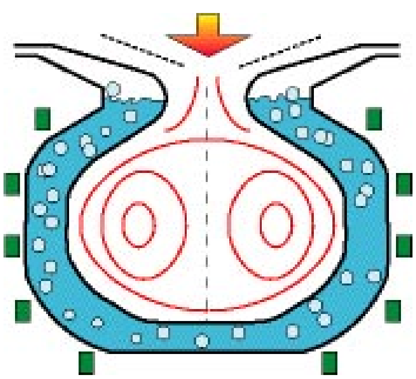


A next experimental step will be quite small.

Experiments



An advanced spheromak will address reactor-relevant physics and technology. (Conceptual design from Lawrence Livermore National Laboratory).



A spheromak power plant—the simple geometry offers opportunities for innovative power production, such as a flowing liquid metal “blanket” for heat removal.

The Compact Torus Experiment (CTX) at Los Alamos National Laboratory in the 1980s achieved high plasma temperatures.

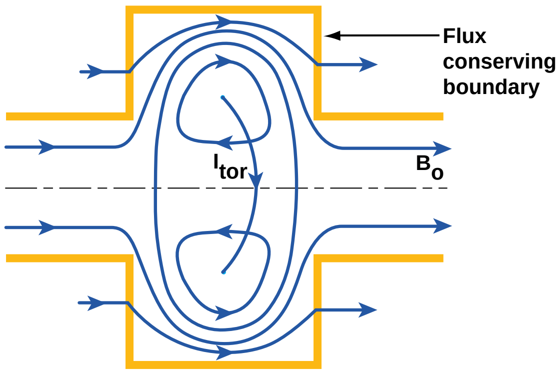
Spheromak-relevant research is under way at:

- University of Manchester, United Kingdom.
- University of Tokyo and Himeji Institute of Technology, Japan.
- Small-scale research at Princeton Plasma Physics Laboratory, Swarthmore College, North Carolina State University, University of California at Berkeley, California Institute of Technology, and University of California at Davis.

The Field-Reversed Configuration (FRC)

Magnetic Topology

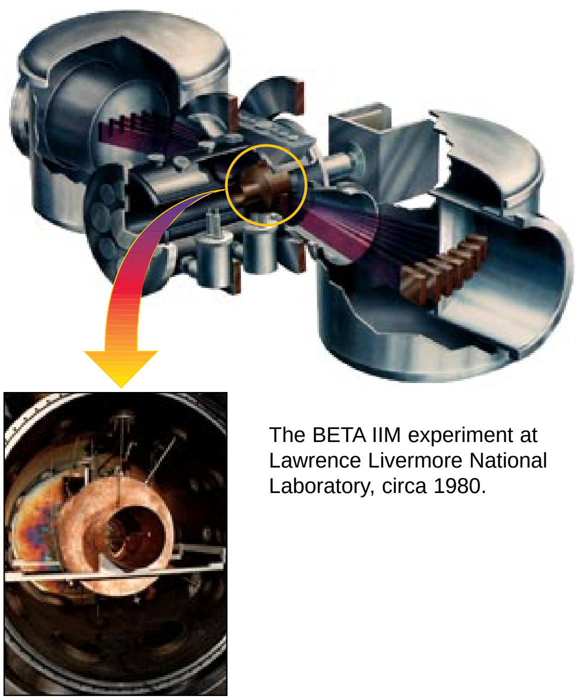
The FRC has a very simple field topology because there is no toroidal field. It has a toroidal current ring embedded in a simple magnetic "mirror" (those fields entering at the left of the diagram and exiting to the right).



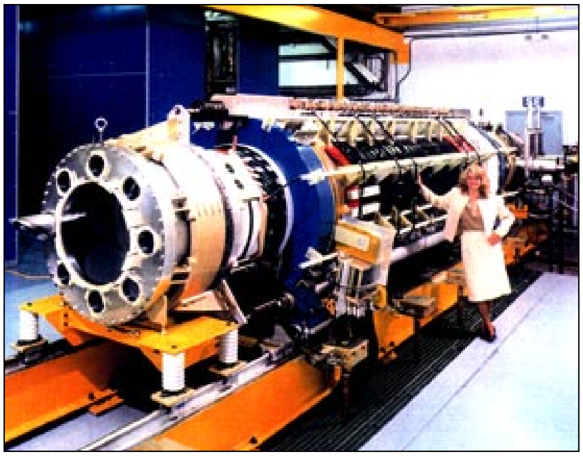
Advantages

- Compact.
- High power density.
- Natural power exhaust channel (direct energy conversion is possible).
- Low internal magnetic field (possible use of advanced fuels).

Experiments

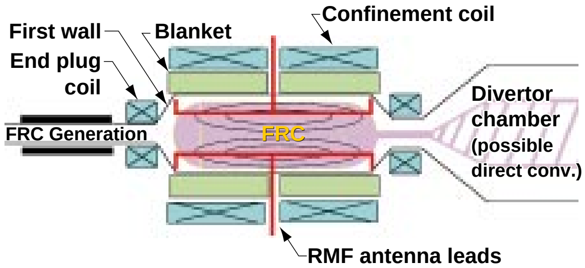


The BETA IIM experiment at Lawrence Livermore National Laboratory, circa 1980.

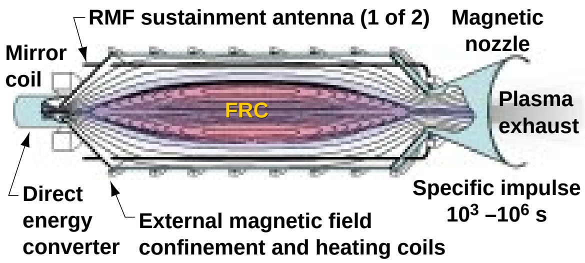


The LSX experiment under way at the University of Washington.

An FRC Power Plant



Other Applications

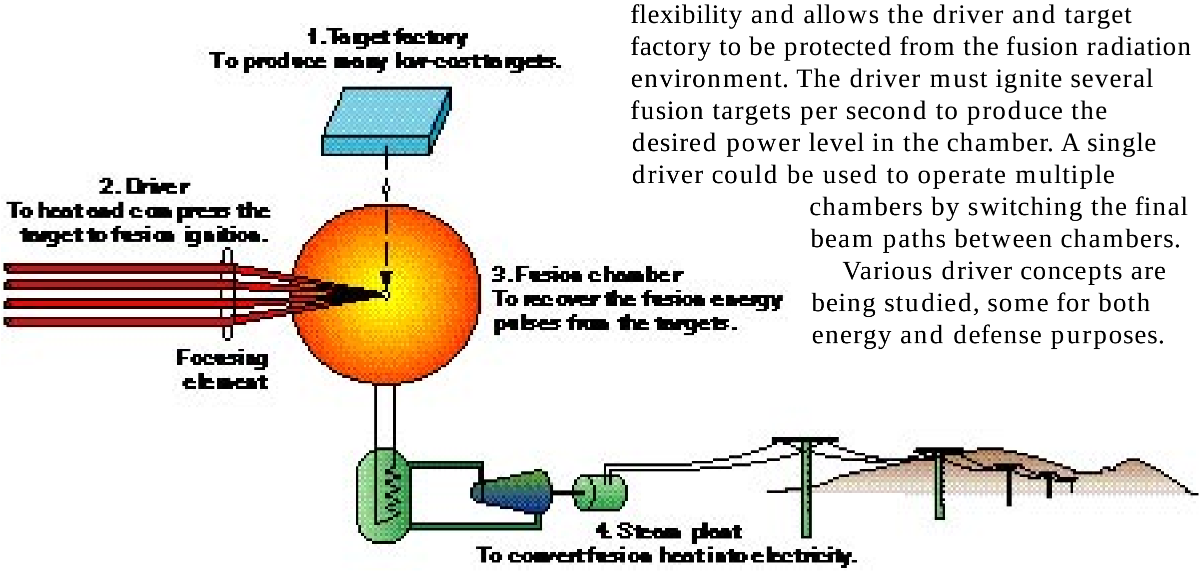


An advanced propulsion scheme for NASA.

Inertial Fusion Energy

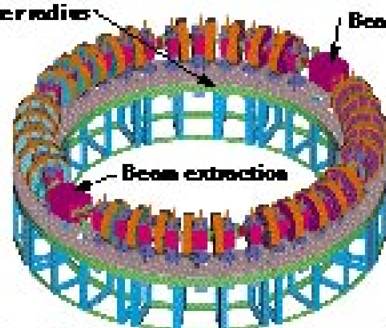
In inertial fusion energy (IFE), a “driver” focuses beams of accelerated ions or intense laser light on a “target” filled with hydrogen fuel. An IFE power plant would have separate areas for the driver, a factory for making the targets, a target chamber where the fusion reactions occur, and a steam turbine to generate electricity. This separability provides design flexibility and allows the driver and target factory to be protected from the fusion radiation environment. The driver must ignite several fusion targets per second to produce the desired power level in the chamber. A single driver could be used to operate multiple chambers by switching the final beam paths between chambers.

Various driver concepts are being studied, some for both energy and defense purposes.

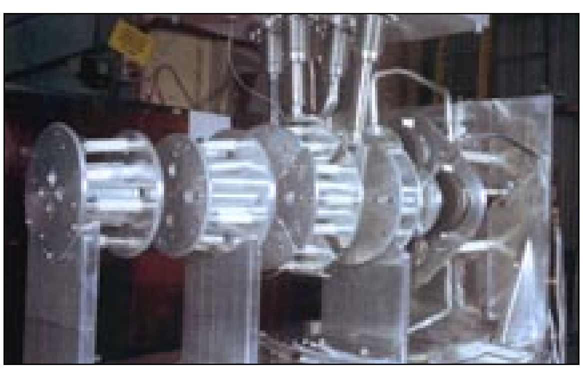


Heavy-ion driver

Because of the need for electrical efficiency and for rapidly repeated firings, one leading approach is to use beams of heavy ions, from either a linear or a circular accelerator. This illustration shows proof-of-principle configuration for a new type of circular accelerator for very-high-beam currents.



Ring with 40 induction acceleration sections



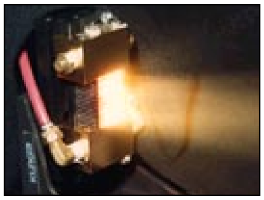
Beam-combiner experiment. Diodes and electrostatic quadrupole for the upcoming four-beam combiner experiment at Lawrence Berkeley National Laboratory. (Shown before installation.)

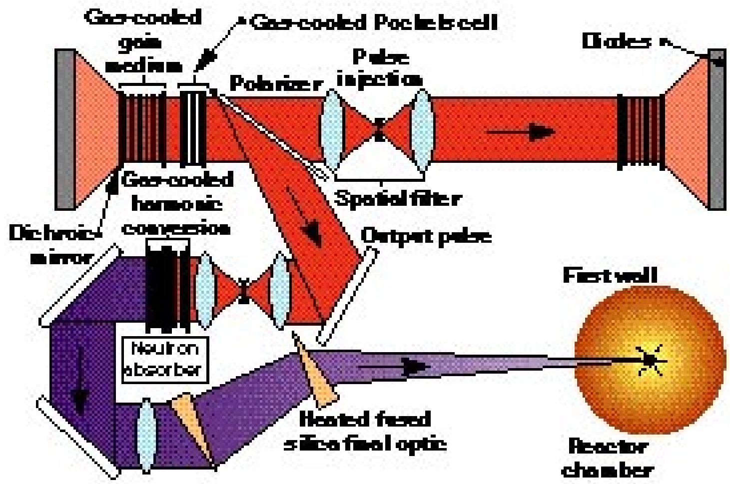
Linear magnetic-transport experiment. Recent scaled experiments at Lawrence Livermore National Laboratory tested the injection, matching, and magnetic transport of a potassium-ion beam.

Other IFE Driver Concepts

Diode-pumped solid-state laser driver

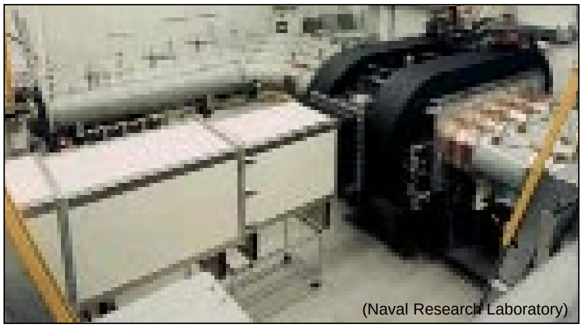
Using diodes instead of flashlamps to pump a solid-state laser could permit the rapidly repeated firings and efficiency necessary for power generation. The laser diode array shown was developed at Lawrence Livermore National Laboratory.





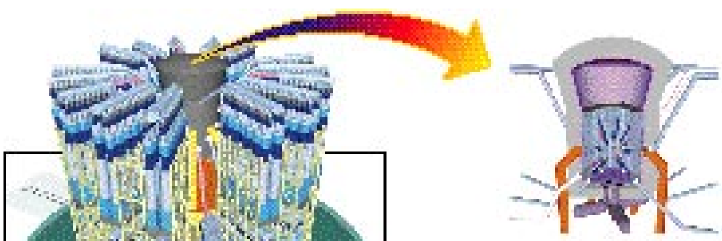
Krypton-fluoride gas laser driver

With the KrF laser, the laser medium is a gas that can be circulated for heat removal in high pulse-repetition-rate applications such as IFE. Target physics experiments are being conducted at the Naval Research Laboratory using the Nike KrF laser. Shown here are the large black magnetic field coils used to guide electron beams through the KrF amplifier cell.

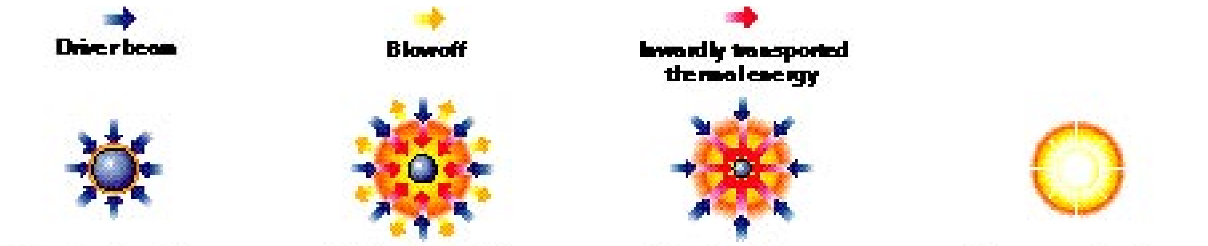

(Naval Research Laboratory)

Light-ion driver

Light-ion accelerators are dominated by the pulsed-power hardware used to produce high currents of light ions such as lithium. Conceptual designs of IFE power plants using light-ion drivers have been completed by the University of Wisconsin and Sandia National Laboratories, New Mexico.



How inertial fusion works

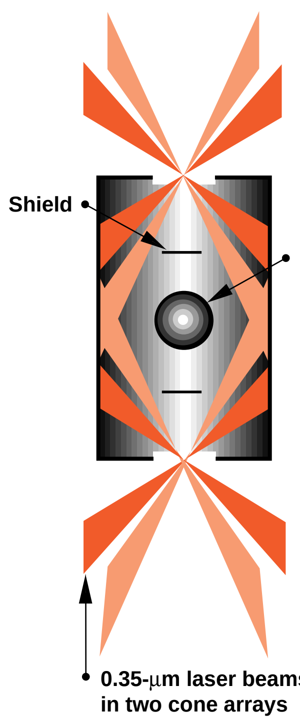


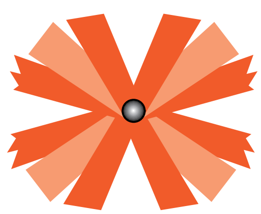
IFE Target Research

In IFE, the fusion reactions occur within a small capsule containing the deuterium-tritium (DT) fuel, and each driver concept requires specific targets and related mechanisms. In "indirect drive" targets, the laser or ion beams do not strike the target capsule directly but enter a metal cylinder and create thermal x-rays when their energy strikes the cylinder walls; it is the x-rays that heat the surface of the fusion capsule. With "direct drive" targets, the beams are focused directly on the target capsule.

Targets for solid-state laser

In the indirect target at left, the outer metal cylinder of gold or lead contains a plastic fusion capsule (about 3 mm in diameter) that is lined with a solid layer of fuel and that holds a small amount of DT gas. Laser beams enter the cylinder in two conical arrays. A direct drive target is shown below.

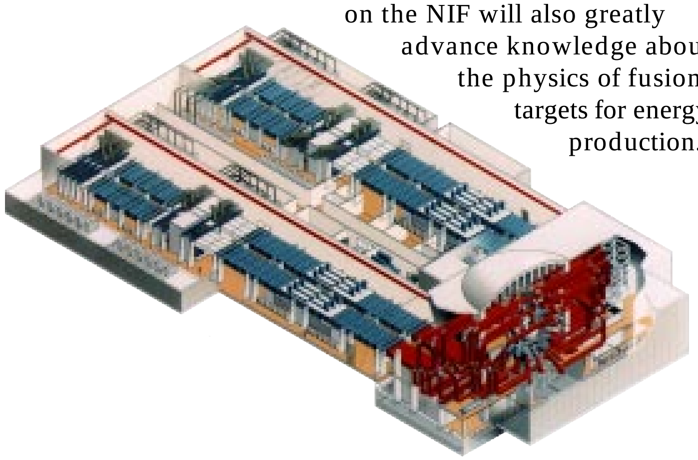




Direct-drive laser target

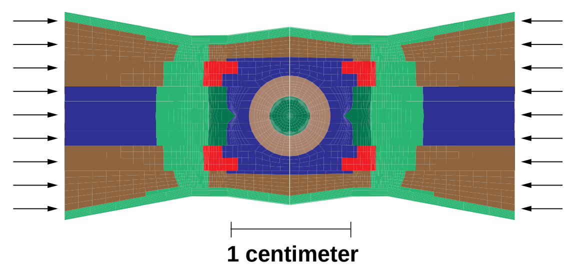
Target physics research at NIF

The National Ignition Facility will prove inertial ignition and energy "gain" —that is, more energy will be released than is required to cause the fusion reactions. Research performed on the NIF will also greatly advance knowledge about the physics of fusion targets for energy production.



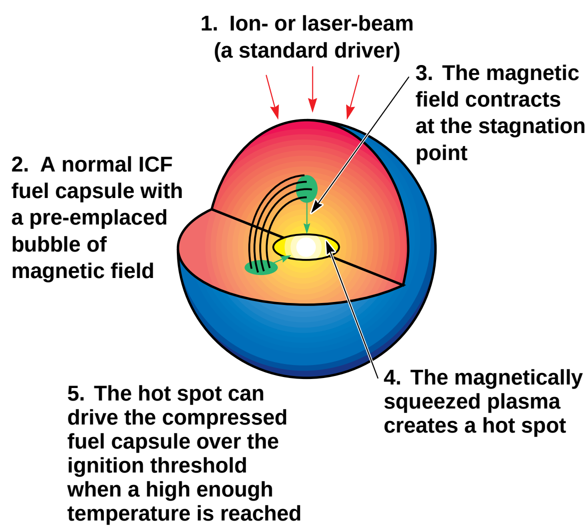
Target for heavy-ion driver

In the heavy-ion target, the plastic fuel capsule is completely surrounded by materials that first convert the ion energy into x rays and then contain the x rays in the volume surrounding the capsule.



Magnetic fast-ignition targets

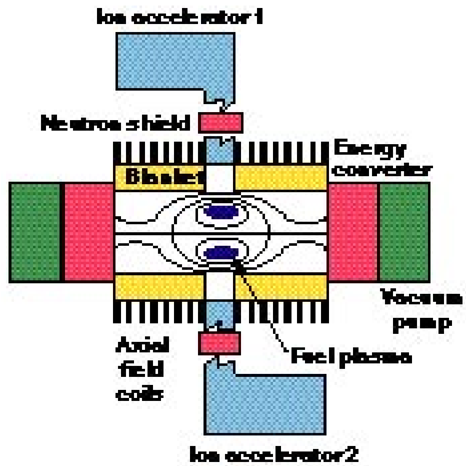
Computer modeling at Lawrence Livermore National Laboratory indicates that an emplaced magnetic field within an inertial-fusion fuel capsule can drive a "hot-spot ignition burn" with only modest compression.



Other Fusion Concepts

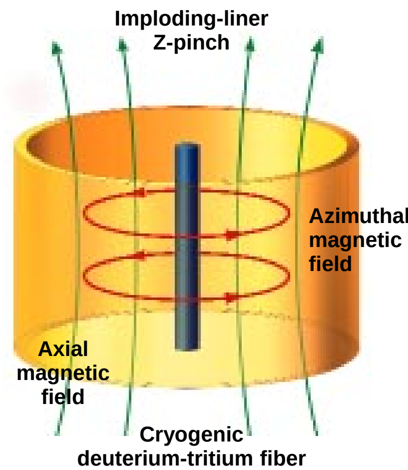
Colliding Ion Beam Reactor Concept

Based on a modified large-orbit field-reversed configuration, this concept uses an efficient direct energy-conversion process. Prelimimary theory indicates that it may have the advantages of a simple geometry, small reactor size, enhanced confinement, and a high power density. If validated in future experimental programs, this simple, low-cost reactor concept would yield a shorter and cheaper development path. Research is being performed at the University of California at Irvine and at Cornell University.



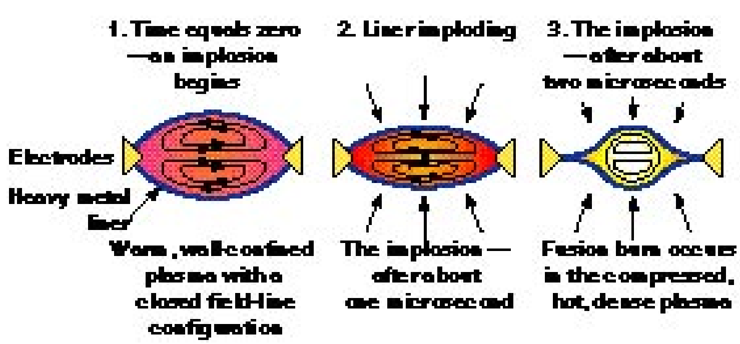
Magneto-Hydrodynamic Inertial Fusion Concept

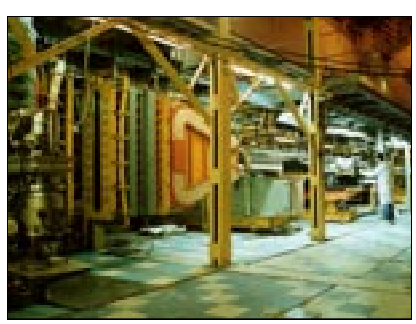
As an imploding liner accelerates toward a centrally located deuterium- and tritium-containing fiber, the magnetic field compresses at extremely high speed, and the target is heated very rapidly. The benefits of this concept include energy transfers with the appropriate time scales for fusion reactions, a magnetic/field target arrangement that reduces instabilities, and a driver that uses far less energy than needed for conventional laser-driven inertial fusion energy. The small size of the experimental equipment reduces costs and will facilitate a fast evaluation. Work on this concept is being conducted at the University of California at Irvine and Riverside.



Wall-Confined Magnetically Insulated Concept

A dense fusion plasma is confined by direct mechanical contact with a material wall. To achieve a pulsed fusion burn, the wall is imploded within a few microseconds onto the plasma. Los Alamos National Laboratory has an experimental collaboration with Russia on the MAGO wall-confined system at Arzamas 16, and Lawrence Livermore National Laboratory is conducting modeling studies.

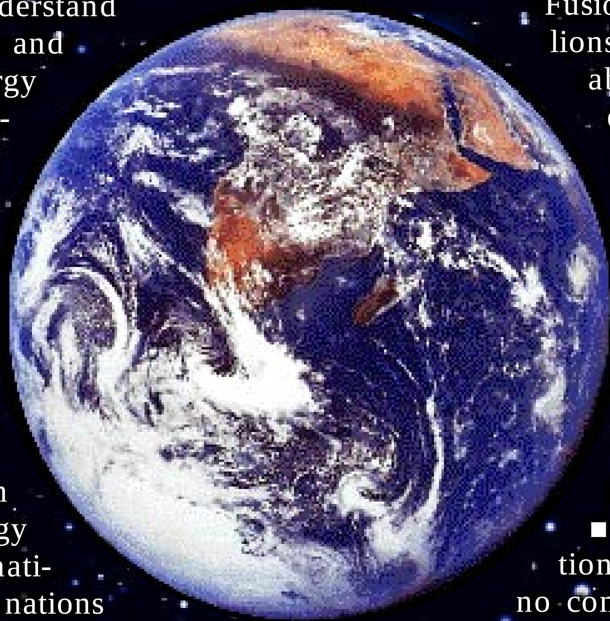




The GOL-3M experimental device, designed to study wall-confined plasmas, was recently completed at Russia's Novosibirsk Institute of Nuclear Fusion.

Sustainable Energy for 21st Century

All of the starlight in the universe is from fusion processes. Fusion is sought on earth as a safe, sustainable, and environmentally benign source of energy for the world. It is important both to understand fully the science of fusion and to develop it as an energy source. Fusion will be universally available and essentially inexhaustible.



World population is expected to burgeon in the next century—from 5.7 billion in 1994 to perhaps 11 to 13 billion by 2100—with much of that growth in the developing countries. Even with increased efficiency, energy demand will grow dramatically as the developing nations create the power and transportation systems essential to a modern economy.

Fossil fuels now supply 85% of the world's primary energy. Burning these fuels releases carbon dioxide and various contaminants into the atmosphere, causing environmental damage and potentially contributing to shifts in the global climate. Furthermore, as oil and natural gas reserves are depleted, sustainable energy sources will be needed.

Fusion fuel would last for millions of years. Deuterium is abundant and is easily extracted from ordinary water. Tritium can be made from lithium, a plentiful element widely distributed on earth. One pound of fusion fuel will produce the same energy as 14 million pounds of coal.

Other major advantages include:

- No chemical combustion products, and therefore no contribution to acid rain or global warming.
- Materials and by-products would be unsuitable for weapons production.
- Radiological hazards are hundreds of times less than from fission.
- No runaway reactions are possible.

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